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DIOXETANE CHEMILUMINESCENCE. THE EFFECT OF DEUTERIUM SUBSTITUTI--ETC(U)  
JAN 77 J KOO, G B SCHUSTER

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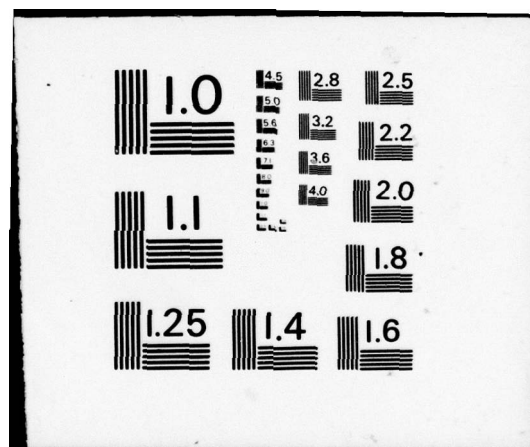
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Dioxetane Chemiluminescence. The Effect  
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by

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20. Abstract...

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Abstract: trans-Diphenyl-1,2-dioxetane was prepared by cyclization of the corresponding  $\beta$ -bromohydroperoxide. Thermal decomposition of this compound proceeds with an activation energy of  $23 \pm 1.6$  kcal/mol to yield benzaldehyde  $10 \pm 2\%$  of which was in an excited triplet state. The effects of replacement of a dioxetane ring proton with a deuterium were investigated. No detectable partitioning between electronically excited protio and deutero benzaldehyde was detected. The secondary deuterium isotope effect on the rate of thermal decomposition of this dioxetane was found to be  $1.01 \pm .02$ . We suggest that the absence of an isotope effect is consistent only with a stepwise decomposition for 1,2-dioxetanes.

The discovery that 1,2-dioxetanes are isolable molecules that thermally decompose to produce high yields of electronically excited carbonyl compounds ushered in a new era of research into chemiluminescent processes<sup>1,2</sup>. Since the initial observations, investigators have probed the structural dependency of this remarkable reaction in an attempt to elucidate, in intimate detail, the conversion of ground state starting material to electronically excited states of the products.

Two fundamental mechanistic schemes have emerged for dioxetane decomposition. The first, originally considered by McCapra<sup>3</sup> and Kearns<sup>4</sup>, postulates simultaneous cleavage of both the oxygen to oxygen and the carbon to carbon bonds of the dioxetane in a concerted manner to directly generate electronically excited products. Later, Turro<sup>5</sup> expanded this picture by suggesting that a spin multiplicity change occurred coincidentally with bond cleavage thereby rationalizing the observation that carbonyl triplet states predominate from dioxetane reactions. MINDO/3 calculations have supported this sequence.<sup>6</sup> The second general mechanistic scheme was advanced by Richardson<sup>7</sup>. This approach favors a stepwise reaction passing through the intermediate 1,4-biradical formed by cleavage of the oxygen to oxygen bond of the strained four membered ring peroxide. The intermediate thus formed is then postulated to partition between excited state carbonyl products of both singlet and triplet multiplicity and ground state carbonyl products.

The concerted mechanism enjoys widespread appeal because it nicely rationalizes the formation of electronically excited products. Simple orbital symmetry correlation arguments predict that the geometrically permissible suprafacial retrocycloaddition mode would result in a crossing of ground state and lower excited state potential energy curves during the



reaction.<sup>4,8</sup> However, experimental evidence is beginning to accumulate that favors the biradical mechanism.

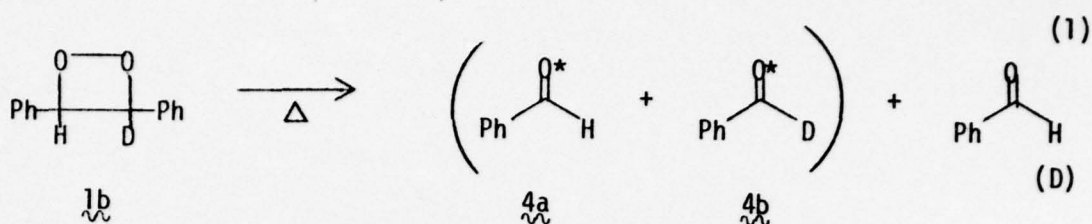
Of the fundamental approaches available to probe the order of bond forming or breaking steps in a non-polar cycloaddition process, substituent effects, identification of intermediate, and effects of isotopic substitution are applicable to dioxetanes. Two types of substituent effects have been employed to probe the dioxetane decomposition mechanism. In a well-planned series of experiments, Richardson<sup>7</sup> has examined the electronic effect of phenyl substituents on the stability of 1,2-dioxetanes. These results are interpreted as being consistent with a stepwise decomposition. The effect of the steric bulk of substituents was probed with the remarkably stable adamantylidene adamantane dioxetane.<sup>9</sup> These results may also be interpreted in terms of a biradical mechanism. In a recent report, differential quenching experiments have also been explained in terms of a biradical intermediate on the path to electronically excited states from dioxetanes.<sup>10</sup>

A key step, common to both the concerted and stepwise fragmentation of dioxetanes, is the conversion of an energetic transition state to an electronically excited state species. This fundamentally important step has been analyzed by Dougherty and others<sup>11</sup> in terms of the separability of nuclear and electronic motions (the Born-Oppenheimer Approximation). In this analysis, a breakdown of the Born-Oppenheimer Approximation is postulated to occur when the energy separating two electronic states becomes very small. One consequence of this breakdown is that the two nearly isoenergetic states are mixed together by vibronic motions of the nuclear skeleton. Of course, this mixing of states is just what is required to convert a transition state for dioxetane cleavage to an excited state of the carbonyl compound product.



If the vibrations of the nuclear framework are in fact important to excited state formation, it should be demonstrable with substituent effects. Experimental evidence of these special substituent effects was available at the outset of this work. A comparison of the chemiluminescent reaction of tetramethyldioxetane (2) with di-n-butylldimethyldioxetane (3) revealed some startling differences. First, the ratio of triplet to singlet excited states from 2 was reported to be ca. 50:1 while the multiplicity ratio from 3 was reported to be 1:3.<sup>12</sup> Subsequent to our initiation of this work, a report appeared revising the multiplicity ratio for dioxetane 3 so that it was consistent with tetramethyldioxetane 2.<sup>13</sup> Second, the total yield of excited states from 2 is claimed to be ca. 50% while the yield of excited states from 3 is claimed to be ca. 3%. Such a dramatic difference between dioxetanes 2 and 3, we felt, was too large to explain with the electronic and steric differences normally resulting from replacement of a methyl group with an aliphatic alkyl group.<sup>14</sup> Therefore, this difference might be a manifestation of the predicted nuclear vibrational coupling effect. Our work (vide infra) has confirmed the value for the yield of excited states from 2.

One aspect of the results reported herein concerns the investigation of the deuterium isotope effect on the rate of decomposition of trans-3,4-diphenyl-1,2-dioxetane (1a). The results of this investigation provide further convincing evidence for the biradical mechanism for retrocycloaddition of 1,2-dioxetanes. A second aspect concerns a test of Born-Oppenheimer breakdown prediction. Thermolysis of deuterated dioxetane 1b was anticipated to form excited benzaldehydes (4a,b) with and without a deuterium (equation 1). Different efficiencies for



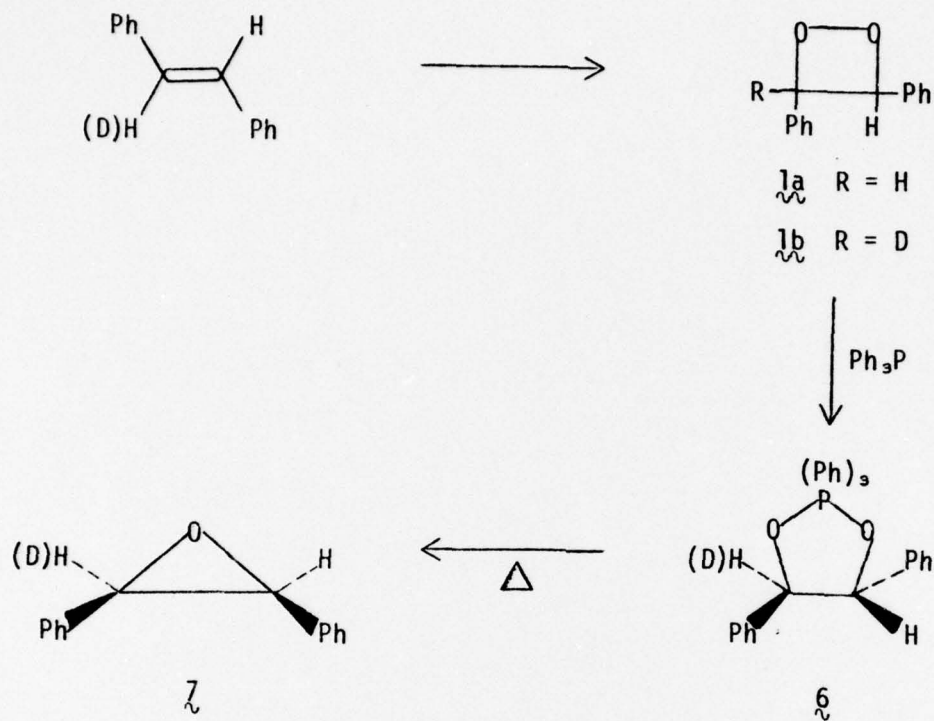
formation of protio and deuterio benzaldehydes could then be taken as evidence that nuclear vibrations were important in controlling excited state production. Isotopic substitution is expected to vary the nuclear vibrations in a well defined manner.

Results: Preparation and Analysis of Deuterated Dioxetane 1.

The preparation of trans-3,4-diphenyldioxetane (**1a**) and trans-3,4-diphenyldioxetane-3-d<sub>1</sub> (**1b**) was accomplished by modification and application of known synthetic procedures. Reduction of deoxybenzoin with LiAlD<sub>4</sub> followed by acid catalyzed dehydration of the alcohol resulted in trans-stilbene-d<sub>1</sub>. NMR and mass spectral analysis indicated that the stilbene was of at least 98% isotopic purity. Formation of the  $\beta$ -bromohydroperoxide **5** was accomplished by the usual procedure of reaction of the olefin with dimethyldibromohydantoin and hydrogen peroxide.<sup>15</sup> Ring closure of **5** to dioxetane **1** was accomplished in ca. 70% yield by employing a two phase base promoted technique. This sequence of reactions is outlined in Scheme 1 and detailed in the Experimental Section.

Dioxetane **1** was probed as to both its stereochemistry and the deuterium incorporation in **1b**. NMR analysis of CCl<sub>4</sub> solutions of dioxetane **1b** indicated that it was at least 98% monodeuterated. Reaction of **1b** with triphenylphosphine resulted in the isolation of the relatively stable posphorane **6**.<sup>16</sup> NMR analysis of **6** indicated a deuterium incorporation of at least 98%. Thermolysis of **6** resulted in the predominant formation of cis-stilbene oxide<sup>17</sup> (**7**). This

Scheme I





observation establishes that the phenyl groups of dioxetane  $\text{I}$  have a trans orientation. NMR spectral analysis of  $\text{I}$  confirmed the deuterium incorporation. This sequence of reactions is outlined in Scheme 1.

#### Chemiluminescent Properties of Dioxetane I.

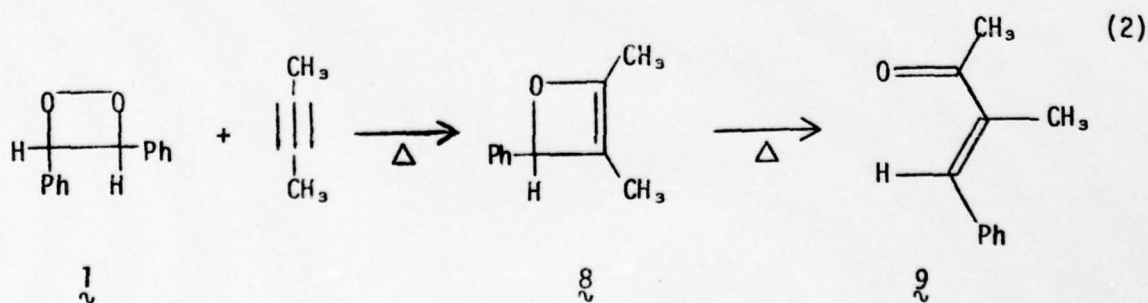
A thorough investigation of the properties of dioxetane  $\text{I}$  establishes that this dioxetane is typical of most that have been prepared and investigated.<sup>18</sup> Therefore only the results that are relevant to our isotopic analysis are reported here.

The activation energy ( $E_A$ ) for the thermal decomposition of  $\text{I}$  in  $\text{CCl}_4$  was determined by two different techniques. First, the total rate of disappearance of dioxetane  $\text{I}$  was determined at several temperatures by monitoring the chemiluminescent decay. Standard Arrhenius analysis of the derived rate constants (see Experimental Section) yielded an  $E_A$  of  $23.6 \pm 1.6$  kcal/mol and a pre-exponential factor of  $10^{12.9}$ . Second, we employed the previously described step analysis<sup>19</sup> to obtain  $E_A$  specifically of the reaction producing electronically excited states. Correction for the temperature dependence of the luminescence efficiency of the 9,10-dibromoanthracene used in this analysis<sup>20</sup> gave an  $E_A$  of  $22.3 \pm 1.9$  kcal/mol. An important implication of the identical  $E_A$  value from both methods of analysis is that both the path leading to excited state formation and the path leading to only ground state products have the same rate determining step.

The multiplicity of the excited state of benzaldehyde formed from thermolysis of  $\text{I}$  was assigned by both spectral comparison and lifetime determination. The observed chemiluminescent emission spectrum from  $\text{I}$  is shown in figure 1. It is identical with the phosphorescence spectrum of photoexcited benzaldehyde. Furthermore, the emission could be quenched with low concentrations of acrylonitrile. All of the bands in the spectrum

were quenched at the same rate indicating that there was no residual fluorescence. The lifetime of benzaldehyde excited state was determined using standard Stern-Volmer quenching techniques<sup>21</sup> to be ca. 0.1 usec at 29.5° in CCl<sub>4</sub> solution. This lifetime is inconsistent with the excited singlet state of benzaldehyde and establishes that the triplet state is responsible for the chemiluminescence.<sup>22</sup>

The important issue of the yield of benzaldehyde excited states from the decomposition of  $I_2$  was resolved by two independent techniques. First, the triplet benzaldehyde formed during the thermal reaction was chemically trapped with 2-butyne. The photochemical reaction of benzaldehyde and 2-butyne has been previously reported to proceed through the oxetene (8) formed via a 2+2 cycloaddition.<sup>23</sup> Thermal rearrangement of the oxetene at room temperature generated the (E)-enone (9) exclusively<sup>24</sup> (equation 2). This trapping reaction is specific for benzaldehyde triplet, no other species would be capable of forming enone 9. This observation eliminates considerable ambiguity present in other systems. The quantum yield of photochemical enone formation was determined to be  $0.60 \pm .05$  under conditions where every benzaldehyde triplet was quenched by 2-butyne. The Type II reaction of valerophenone in hexane/t-butyl alcohol was used as the actinometer.<sup>25</sup> Quantitative trapping of the benzaldehyde excited states generated from decomposition of  $I_2$ , under conditions identical to the photochemical quantum yield experiment, indicated that the yield of benzaldehyde triplet from  $I_2$  was  $10 \pm 2\%$ .





The second technique used for estimation of the yield of excited states from  $\text{1}$  was the comparison of luminescent intensity of  $\text{1}$  and tetramethyldioxetane ( $\text{2}$ ). The yield of electronically excited acetone from  $\text{2}$  has previously been reported to be ca. 50%<sup>5</sup>. We compared dioxetanes  $\text{1}$  and  $\text{2}$  under conditions where energy transfer from the chemically formed carbonyl excited states to DBA is expected to occur.<sup>26</sup> The sensitized DBA emission was electronically integrated for more than five half-lives for both dioxetanes. The integrated total luminescent intensity as a function of DBA concentration was determined and extrapolated to infinite DBA concentration for both dioxetanes. The total light emission from  $\text{2}$  was  $3.0 \pm 0.5$  times the emission from  $\text{1}$  at infinite DBA concentration in both  $\text{CCl}_4$  and benzene, consistent with our determination of the yield of  $\text{1}$  and the previous measurement for  $\text{2}$ .

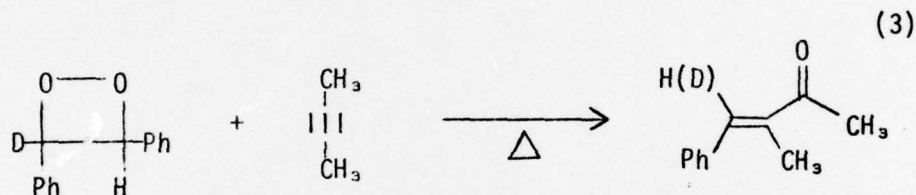
#### Effect of Isotopic Substitution on Dioxetane 1.

As noted above, two distinct phenomena can be probed by the introduction of a deuterium into dioxetane  $\text{1}$ . We have investigated the effect of isotopic substitution on the rate of thermal decomposition of dioxetane  $\text{1}$  and have probed the influence of the deuterium in directing excited state formation.

The thermal decomposition of dilute solutions of  $\text{1a}$  and  $\text{1b}$  is strictly first order for more than six half-lives. Since the chemiluminescent intensity was found to be directly proportional to the dioxetane concentration, and the chemiluminescence could be continuously monitored, very precise first order rate constants for reaction of  $\text{1a}$  and  $\text{1b}$  could be obtained. The results of this study are summarized in Table 1. These data indicate that, within experimental error, the rate constants for unimolecular decomposition of dioxetanes  $\text{1a}$  and  $\text{1b}$  are identical. That is, the secondary deuterium isotope effect for unimolecular reaction of

these dioxetanes ( $k_H/k_D$ ) is  $1.01 \pm 0.02$ . Furthermore, comparison of the total integrated luminescent intensity from  $\underline{1a}$  and  $\underline{1b}$  revealed no isotopic dependency.

Investigation of isotopic selection of the location for the excitation energy was probed with a trapping reaction. Each deuterated dioxetane  $\underline{1b}$  that fragments can form at most one electronically excited benzaldehyde. The excited benzaldehydes produced were quantitatively trapped with 2-butyne (*vide supra*). Any predilection toward protio or deuterio excited benzaldehyde formation would be reflected in the deuterium incorporation in the isolated enone  $\underline{9}$ , (equation 3).




It was shown that under the conditions of the experiment, the trapping reaction was equally efficient for both deuterated and undeuterated benzaldehyde. Mass spectral and NMR analysis of the enone formed from reaction of deuterodioxetane  $\underline{1b}$  revealed a deuterium incorporation of 48%. Correction for the deuterium content of  $\underline{1b}$  revealed that there was no preferential formation of either isotopic benzaldehyde. Thus, there was no isotopic influence on the selection of the location for the excitation energy at the transition state for excited state formation.

#### Discussion

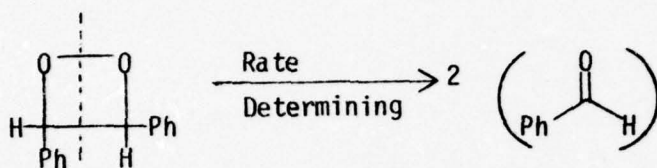
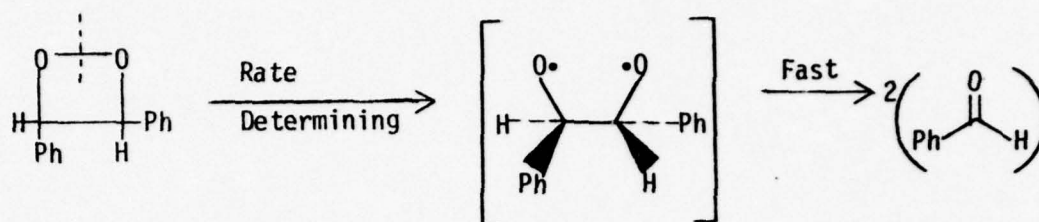
The study of the chemistry of dioxetane  $\underline{1}$  and the effect of deuterium substitution on it has revealed several important features about dioxetane chemiluminescence. First, the observed absence of a measurable secondary deuterium isotope effect on the rate of formation of benzaldehyde from  $\underline{1}$  places some important constraints on the nature of the rate determining step for this reaction.

Secondary deuterium isotope effects have been analyzed by Streitwieser and coworkers by statistical mechanics.<sup>26</sup> They conclude that the major influence of the isotopic substitution on the rate of reaction is through a change in an "out-of-plane" C-H bending vibration. They observed that this vibrational mode was very sensitive to the hybridization of the isotopically substituted carbon. This model predicts that a change from  $sp^3$  to  $sp^2$  hybridization of the isotopically substituted carbon should give rise to a secondary deuterium isotope effect of ca. 1.38. Experimental verification of this prediction has been forthcoming. Investigation of the deuterium isotope effects in solvolytic substitution at saturated carbons has routinely revealed isotope effects of about 12% per deuterium atom.<sup>27</sup> A study of the secondary deuterium isotope effects on the radical polymerization of styrene indicated that the magnitude of the effect was the same in non-polar reactions as for the polar solvolyses.<sup>28</sup> Perhaps of more relevance to the current investigation are reports of the effect deuterium substitution on the rate of 2+2 cycloaddition reactions. Baldwin<sup>29</sup> studied the effect of deuterium substitution on the rate of the cycloaddition reaction of diphenylketene with styrene. A secondary deuterium isotope effect ( $k_H/k_D$ ) of 0.91 was observed when the styrene was substituted with a deuterium at the  $\beta$ -position. This observation was interpreted to imply that the  $\beta$ -carbon of styrene progressed from  $sp^2$  toward  $sp^3$  hybridization as the transition state for this reaction was approached. Similar effects of isotopic substitution were observed by Dolbier<sup>30</sup> during an investigation of allene 2+2 cycloaddition reactions.

Consider the two mechanisms advanced for the thermal fragmentation of dioxetanes to carbonyl compounds (Scheme II). For the concerted mechanism, the isotopically substituted carbon of dioxetane  undergoes a change



Scheme II



in hybridization from  $sp^3$  toward  $sp^2$  as the reaction approaches the transition state. Theory predicts, and experiments confirm, that this change in hybridization should lead to an observable normal secondary deuterium isotope effect. On the other hand, for the stepwise mechanism in which cleavage of the oxygen-oxygen bond of the dioxetane is the rate determining step, no change in hybridization at the isotopically substituted carbon is anticipated. Thus, this sequence for bond breaking is not expected to give rise to an observable isotope effect. Our results are consistent only with the stepwise mechanism for fragmentation of 1,2-dioxetanes.

The lifetime of carbonyl triplet excited states in rigid media at low temperature have been found to be dependent upon isotopic substitution.<sup>31</sup> The lifetime of benzaldehyde triplet in EPA at 77°K was found to depend upon isotopic substitution at the aldehyde carbon.<sup>32</sup> Furthermore, spectroscopic investigation of benzaldehyde has revealed that the aldehydic hydrogen plays an important, if not dominant, role in the radiationless deactivation of the electronically excited triplet state.<sup>33</sup> These effects of deuterium substitution have been attributed to the difference in the spacing of the vibrational levels of the carbon-hydrogen and carbon deuterium bonds.<sup>34</sup> That is, at constant vibrational excitation energy, the deuterium substituted compound would be at a considerably higher vibrational quantum number than the hydrogen substituted compound. The vibrational quantum number is postulated to influence the overlap between the wavefunctions describing the ground and electronically excited state of the chromophore<sup>34</sup> and hence the rates of interconversion between these states. A chemiluminescent reaction is a conversion between electronic states. Furthermore, the model for this conversion proposed by Dougherty (vide supra) takes specific



account of vibrations of the nuclear skeleton. Monodeuterated dioxetane  $\text{C}_2\text{H}_4\text{D}_2$  provides an ideal system for examining these ideas.

If coupling, of any form, between the vibrations of the substituents on the carbons of dioxetanes and the electronically excited state produced is important to the change in state, then deuterated dioxetane  $\text{C}_2\text{H}_4\text{D}_2$  should manifest this influence. We anticipated that  $\text{C}_2\text{H}_4\text{D}_2$  might decompose to yield unequal proportions of protio and deuterobenzaldehyde. In fact, no such selection for the excited state location was observed. The implication of this result is that if vibrational coupling is important in excited state formation from  $\text{C}_2\text{H}_4\text{D}_2$  it cannot in any way involve vibrations of the substituents on carbons.

### Conclusions

The mechanism of thermal decomposition of 1,2-dioxetanes to form electronically excited carbonyl compounds is central to an understanding of chemiluminescent phenomena. If indeed a prerequisite to efficient chemical formation of excited states is a concerted "forbidden" pericyclic process, then the number of potential chemiluminescent systems is clearly limited. Our work, and the work of others<sup>7,9,10,13,14</sup>, strongly suggests that an intermediate chemical species precedes formation of the triplet excited carbonyl compounds characteristic of dioxetane thermolysis. In particular, the absence of a measurable secondary deuterium isotope effect reported herein convincingly demonstrates that the hybridization at carbon is not changing during the rate determining step of this reaction. This result is clearly consistent only with a stepwise reaction. The implication of this to the chemical formation of electronically excited states in general

is apparent. The search for new efficient chemiluminescent processes should not be limited to reactions predicted to be "forbidden" by conservation of orbital symmetry considerations.

Acknowledgment. This work was supported by the Office of Naval Research.

### Experimental Section

General. All melting points were corrected according to the mp ( $80.1^\circ$ ) of sublimed naphthalene. Nmr spectra were recorded on a Varian Associates A-60A instrument with tetramethylsilane internal standard. IR spectra were obtained with a Beckmann IR-12 Spectrometer. Mass spectra were recorded using a Varian MAT CH-5 Mass Spectrometer. Elemental analyses were performed by the Analyses Laboratory, Department of Chemistry, University of Illinois, Urbana, Illinois.

2-Bromo-1,2-diphenylethyl Hydroperoxide. A solution of trans-stilbene (2.70 g, 0.015 mol) in 40 ml of dry THF was poured into a solution of 90%  $\text{H}_2\text{O}_2$  (28 g, 0.72 mol) in 140 ml of THF which had been dried with anhydrous  $\text{Na}_2\text{SO}_4$  overnight at  $-20^\circ\text{C}$ . 1,3-Dibromo-5,5-dimethylhydantoin (2.5 g, 0.0090 mol, Matheson, Coleman and Bell) was added in several portions to the stilbene solution over a period of 1 hr, at room temperature under nitrogen. The resulting yellow solution was stirred for an additional hour at room temperature under nitrogen. The yellow solution was poured into 500 ml of a cold saturated aqueous solution of  $\text{Na}_2\text{CO}_3$ . The resulting mixture was extracted with diethyl ether (3 x 100 ml). The combined extracts were washed with water and brine, and then dried over anhydrous  $\text{Na}_2\text{SO}_4$  at  $0^\circ\text{C}$ . The volume of the solution was reduced to about 50 ml and any precipitate formed was removed. The hydroperoxide was purified as its DABCO salt using the procedure of Kopecky<sup>15</sup> to give 2.53 g of white solid (57% yield), the nmr spectrum of which indicated the presence of about 95% pure  $\beta$ -bromohydroperoxide. An analytically pure sample was obtained by recrystallization in  $\text{CH}_2\text{Cl}_2$ : mp  $116-118^\circ$ ; nmr ( $\text{CDCl}_3$ )  $\delta$  5.22 (d,  $J = 7$  Hz, 1 H), 5.38 (d,  $J = 7$  Hz, 1 H), 7.22-7.43 (m, 5 H) and 7.90 (broad s, 1 H); ir (KBr) 3498, 1497, 1455, 1343, 1202, 760 and  $700\text{ cm}^{-1}$ .



Anal. Calcd for  $C_{14}H_{13}O_2Br$ : C, 57.36; H, 4.47. Found: C, 57.39; H, 4.40.

Diphenyldioxetane (1a). To a suspension of 2-bromo-1,2-diphenylethyl hydroperoxide (252 mg, 0.861 mmol) in 40 ml of  $CCl_4$  at  $0^\circ$  was added with vigorous stirring, an aqueous solution (20 ml) of KOH (600 mg, 11 mmol). The resulting mixture was stirred vigorously for 1.5 hr at  $0^\circ$  in the dark. The  $CCl_4$  layer was separated and dried over anhydrous  $K_2CO_3$  at  $0^\circ$  for 20 min. The light yellow solution was transferred to a 50 ml volumetric flask. The concentration of the dioxetane in this solution was determined by NMR spectroscopy and iodometric titration to be  $1.25 \pm 0.05 \times 10^{-2} M$  (73% yield). The only other compound in the solution was benzaldehyde with an approximate ratio of 7:1, dioxetane to benzaldehyde. Nmr ( $CCl_4$ );  $\delta$  6.37 (s, 2 H) and 7.36-7.83 (m, 10 H).

1-Deutero-1,2-diphenylethanol. A solution of deoxybenzoin (3.92 g, 0.020 mol, Aldrich) in 40 ml of dry THF was added dropwise to a suspension of  $LiAlD_4$  (0.42 g, 0.010 mol deuterium analysis 18.7%, from Alfa) in 120 ml of dry THF at room temperature with stirring under nitrogen. After the completion of the addition, the temperature of the reaction mixture was raised to  $50^\circ$  for 4 hr. The usual workup gave crude product weighing 3.5 g (90% yield). The nmr spectrum showed only the presence of 1-deutero-1,2-diphenylethanol. The crude product was used without further purification for the synthesis of  $\alpha$ -deuterostilbene. Further purification was achieved by recrystallization in n-hexane; mp  $64-65^\circ$  (lit.  $64.4-65.4^\circ$ )<sup>35</sup>; nmr ( $CDCl_3$ )  $\delta$  2.16 (s, 1 H)(OH), 2.93 (s, 2 H)( $CH_2$ ) and 7.00-7.43 (m, 10 H).

Trans- $\alpha$ -deuterostilbene. 1-Deutero-1,2-diphenylethanol (3.5 g, 0.018 mol) was dissolved in 45 ml of ethanol, 25 ml of Conc. HCl, and 0.5 ml of Conc.  $H_2SO_4$ . The mixture was refluxed for 4 hr and

the white flake precipitate that formed (2.64 g, 83% yield) was collected. The nmr spectrum of the white solid indicated that it was pure trans- $\alpha$ -deuterostilbene; mp 123-124° (lit. 124°)<sup>36</sup>. No depression upon mixture with an authentic sample of undeuterated trans-stilbene was observed. Deuterium content was determined by mass spectrometry ( $98 \pm 1\%$ ) and by nmr assay ( $98 \pm 2\%$ ).

Deutero-diphenyldioxetane (1b). A mixture of 2-bromo-1-deutero-1,2-diphenylethyl and 2-bromo-2-deutero-1,2-diphenylethyl hydroperoxide was obtained in 51% yield from the reaction of trans- $\alpha$ -deutero-stilbene with 1,3-dibromo-5,5-dimethylhydantoin in dry THF in the presence of excess H<sub>2</sub>O<sub>2</sub> following the same procedure as employed in preparing undeuterated 2-bromo-1,2-diphenylethyl hydroperoxide. Nmr (CDCl<sub>3</sub>)  $\delta$  5.23 (s, 1 H), 5.36 (s, 1 H), 7.20-7.47 (m, 10 H) and 8.0 (broad s, 1 H).

The deutero-diphenyldioxetane was obtained in ca. 70% yield using the same procedure employed in the synthesis of the undeuterated dioxetane. Nmr (CCl<sub>4</sub>)  $\delta$  6.34 (s, 1 H) and 7.41-7.80 (m, 10 H). Nmr spectrum of deutero-diphenyldioxetane showed  $98 \pm 2\%$  deuterium content.

4-Deutero-4,5-diphenyl-2,2,2-triphenyl-1,3,2-dioxaphospholane (6). A solution of triphenylphosphine (165 mg, 0.63 mmol) in 5 ml of CCl<sub>4</sub> was rapidly added to 30 ml of  $2.1 \times 10^{-2}$  M deutero-diphenyldioxetane (0.63 mmol) in CCl<sub>4</sub> cooled in an ice-bath. After 20 min the solvent was evaporated and the resulting residue was extracted with 2 ml of cold n-hexane leaving a white solid (280 mg, 93% yield). An analytically pure sample was obtained from recrystallization in ether and n-hexane (1:3). Nmr analysis of the recrystallized phosphorane indicated the presence of the phosphorane and diethyl ether in a ratio of 2:1. The ether could not be removed in high vacuum (0.2 mmHg); mp 85-96°; nmr (CCl<sub>4</sub>)  $\delta$  4.44



(broad s, 1 H) and 6.90-7.95 (m, 25 H); deuterium content was  $98 \pm 2\%$  by nmr assay; ir (KBr) 3070 (w), 1436 (m), 1100-1085 (m), 1044 (m), 1022 (m), 810-796 (m), 754 (m), 720 (m), 700 (s), 600 (m), and 557 (s)  $\text{cm}^{-1}$ .

Anal. Calcd. for  $\text{C}_{32}\text{H}_{26}\text{DO}_2\text{P} \cdot 0.5 \text{ C}_4\text{H}_{10}\text{O}$ : C, 79.82; H, 6.31; P, 6.05. Found: C, 79.79; H, 6.25; P, 5.94.

Undeuterated phosphorane was similarly prepared from the reaction of diphenyldioxetane with triphenylphosphine; nmr ( $\text{CDCl}_3$ )  $\delta$  4.56 (d,  $J = 1 \text{ Hz}$ , 2 H) and 7.0-8.0 (m, 25 H).

Pyrolysis of 4,5-diphenyl-2,2,2-triphenyl-1,3,2-dioxaphospholane. A solution of the phosphorane (161 mg, 0.34 mmol) in 10 ml of  $\text{CCl}_4$  was refluxed for 7 hr under nitrogen. Removal of the solvent and extraction of the residue with 10 ml of n-hexane precipitated triphenylphosphine oxide, 90 mg (95% yield), mp  $154.5\text{-}156^\circ$  (lit.  $155\text{-}156^\circ$ )<sup>16</sup>. The filtrate was concentrated to give an oily residue (60 mg, 90% yield), the nmr spectrum of which indicated the presence of cis-stilbene oxide, trans-stilbene oxide, and deoxybenzoin in a ratio of 74:14:12.

A solution of the deuterated phosphorane (280 mg, 0.59 mmol) was refluxed in a mixture of benzene (7 ml) and dioxane (7 ml) for 7 hr under nitrogen. Following the above procedure gave cis- $\alpha$ -deuterostilbene oxide, trans- $\alpha$ -deuterostilbene oxide and  $\alpha$ -deuterodeoxybenzoin in a ratio of 72:20:9. Deuterium content of the isomers was determined to be at least 98% from nmr assay using mesitylene as internal standard.

Trap of excited benzaldehyde and benzaldehyde-d, with 2-butyne. A solution of deuterio-diphenyldioxetane (30 ml of 0.032 M in  $\text{CH}_2\text{Cl}_2$ , 0.96 mmol) and excess 2-butyne (0.8 ml, 10 mmol, Chemical Samples, Co.) was reacted at room temperature for 20 hr. Evaporation of the solvent, gave benzaldehyde and a small amount of (E)-3-methyl-4-phenyl-3-buten-2-one,

which was purified by gas chromatography (SE-30 8.4%, 4 ft, at 167°). The ratio of protio-(E)-enone to deuterio-(E)-enone was determined to be 52:48 by mass spectrometry. Analysis of deuterium content was done on the M-15 fragment. Control experiments showed that the trapping efficiency for the deuterated and undeuterated benzaldehyde was the same.

Yield of Excited Benzaldehyde from Thermal Decomposition of Diphenyldioxetane. The quantum efficiency of the addition of benzaldehyde triplet to 2-butyne was determined using standard photochemical techniques. Simultaneous (merry-go-round) low conversion (ca. 1%) irradiation of optically dense degassed solutions of benzaldehyde with 2-butyne and valerophenone in hexane/t-butylalcohol with potassium chromate filtered (313 nm) light indicated a quantum efficiency for enone formation of  $0.60 \pm 0.05$ . Quantitative thermal decomposition of dioxetane 1 ( $0.012 \text{ M}$  in  $\text{CCl}_4$ ) with 2-butyne ( $.125 \text{ M}$ ) under conditions identical to the photochemical quantum yield determination indicated the yield of triplet benzaldehyde from 1 to be  $10 \pm 2\%$ .

Determination of the Activation Energy for Thermal Decomposition of 1. The rate constants for thermolysis of diphenyldioxetane 1a were determined in  $\text{CCl}_4$  solution over a  $20^\circ$  range, (Table 2). The emission intensity of sensitized DBA ( $1 \times 10^{-3} \text{ M}$ ) was followed with time. The initial concentration of 1 was  $1 \times 10^{-5} \text{ M}$ .

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Captions for Tables

Table I. Determination of Secondary Deuterium Isotope Effect for  
Dioxetane 1.

Table II. Rate of Thermal Decomposition of Dioxetane 1a.

Caption for Figure

Chemiluminescence Emission Spectrum from Thermal Decomposition of  
Dioxetane 1a.

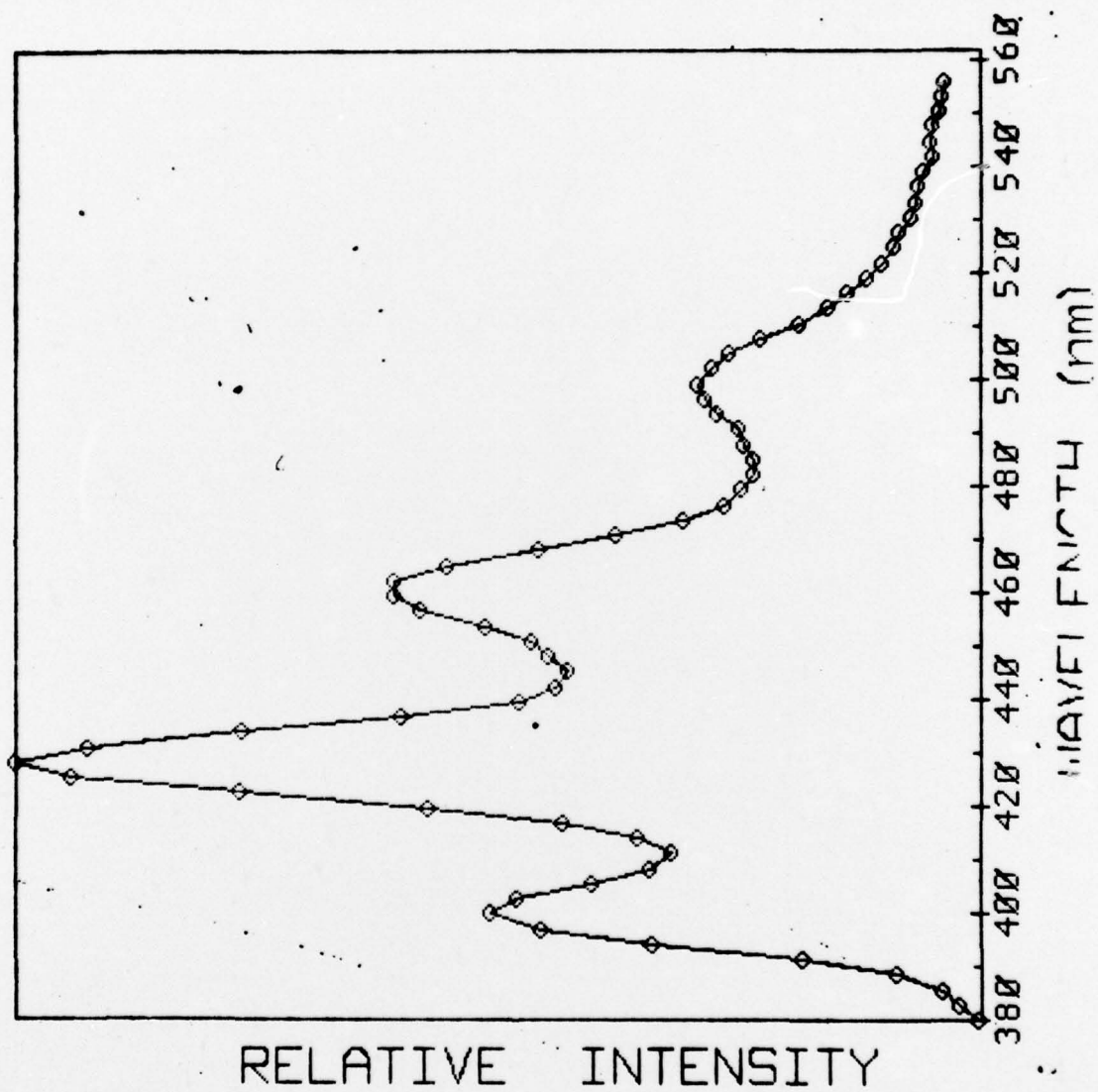
TABLE I

	$k_H \times 10^4 \text{ sec}^{-1}$	$k_D \times 10^4 \text{ sec}^{-1}$	$k_H/k_D$	$\phi_H/\phi_D^a$
Run 1 - BA <sup>b</sup>	$5.25 \pm .01$	$5.13 \pm .01$	1.023	0.93
Run 2 - BA	$5.80 \pm .04$	$5.45 \pm .02$	1.063	0.94
Run 3 - BA	$4.60 \pm .01$	$4.69 \pm .01$	0.981	1.01
Run 4 - BA	$5.42 \pm .02$	$5.32 \pm .01$	1.019	-
Run 5 - BA	$5.22 \pm .01$	$5.39 \pm .03$	0.968	-
Run 6 <sup>d</sup>	$4.14 \pm .02$	$4.07 \pm .01$	1.016	1.00
mean $1.01 \pm .02$				$0.97 \pm .03$

- a. Ratio of total light emission from  $^1a$  and  $^1b$ .  
b. BA = biacetyl, typical conditions:  $[I] = 5 \times 10^{-7} \text{ M}$ ; (BA) =  $5 \times 10^{-3} \text{ M}$ ; in  $\text{CCl}_4$ ; solutions were purged with  $\text{N}_2$  for 3 min at  $0^\circ$ ; temperature ca.  $40^\circ$ , variation between runs ca.  $1.5^\circ$ , within a run less than  $0.1^\circ$ .  
c. All errors are standard deviations.  
d. Determined by monitoring benzaldehyde phosphorescence.  $[I] = 2 \times 10^{-4} \text{ M}$  in  $\text{CCl}_4$ ; aerated; temperature  $40.0 \pm 0.1^\circ$ .

TABLE II

T°C	k <sub>sec</sub> <sup>-1</sup> x 10 <sup>4</sup>	
36.0	2.44 <sup>a</sup>	
40.5	4.63	
51.0	14.0	
54.3	20.2	
57.6	28.3	
59.9	37.1	
63.1	54.9	E <sub>A</sub> = 23.6 ± 1.6 kcal/mol log A = 12.9 ± 0.9
65.3	74.8	





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